

Principles of Forest Management for Enhancing Carbon Sequestration

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The net rate of carbon accumulation has been generally understood (Woodwell and Whittaker, 1968) as the difference between gross primary production (gains) and respiration (losses), although this neglects important processes such as leaching of dissolved organic compounds (DOCs), emission of methane (CH_4), fire, harvests, or erosion that may contribute substantially to carbon loss and gain in forest ecosystems (Schulze *et al.*, 1999; Harmon, 2001; Chapin *et al.*, 2006). The net ecosystem carbon balance (NECB) in forests is, therefore, defined as net ecosystem production, or NEP, plus the non-physiological horizontal and vertical transfers into and out of the forest stand.

With respect to the impacts of forest management on the overall carbon balance, some general principles apply (Harmon, 2001; Harmon and Marks, 2002; Pregitzer *et al.*, 2004). First, forest management can impact carbon pool sizes via:

- changing production rates (since $\text{NEP} = \text{net primary production [NPP]} - \text{heterotrophic respiration [R}_h\text{]}$);
- changing decomposition flows (R_h) (*e.g.*, Fitzsimmons *et al.*, 2004);
- changing the amount of material transferred between pools; or
- changing the period between disturbances/management activities.

The instantaneous balance between production, decomposition, and horizontal or vertical transfers into and out of a forest stand determines whether the forest is a net source or a net sink. Given that these terms all change as forests age, the disturbance return interval is a key driver of stand- and

landscape-level carbon dynamics. R_h tends to be enhanced directly after disturbance, so as residue and other organic carbon pools decompose, a forest is often a net source immediately after disturbances such as management activity. NPP tends to increase as forests age, although in older forests it may decline (Ryan, 1997). Eventually, as stands age, NPP and R_h become similar in magnitude, although few managed stands are allowed to reach this age. The longer the average time interval between disturbances, the more carbon is stored. The nature of the disturbance is also important; the less severe the disturbance (*e.g.*, less fire removal), the more carbon is stored.

Several less general principles can be applied to specific carbon pools, fluxes, or situations:

- Management activities that move live carbon to dead pools (such as coarse woody debris [CWD] or soil carbon) over short periods of time will often dramatically enhance decomposition (R_h), although considerable carbon can be stored in decomposing pools (Harmon and Marks, 2002). Regimes seeking to reduce the decomposition-related flows from residue following harvest may enhance overall sink capacity of these forests if these materials are used for energy generation or placed into forest products that last longer than the residue.
- Despite the importance of decomposition rates to the overall stand-level forest carbon balance, management of CWD pools is mostly impacted by recruitment of new CWD rather than by changing decomposition rates (Janisch and Harmon, 2002; Pregitzer and Euskirchen, 2004). Decreasing the interval between harvests can significantly decrease the store in this pool.
- Live coarse root biomass accounts for approximately

20-25% of aboveground forest biomass (Jenkins *et al.*, 2003), and there is additional biomass in fine roots. Following harvest, this pool of live root biomass is transferred to the dead biomass pool, which can form a significant carbon store. Note that roots of various size classes and existing under varying environmental conditions decompose at different rates.

- Some carbon can be sequestered in wood products from harvested wood, though, due to manufacturing losses, only about 60% of the carbon harvested is stored in products (Harmon, 1996). Clearly, longer-lived products will sequester carbon for longer periods of time.
- According to international convention, the replacement of fossil fuel by biomass fuel can be counted as an emissions offset if the wood is produced from sustainably managed forests (Schoene and Netto, 2005)

Little published research has been aimed at quantifying the impacts of specific forest management activities on carbon storage, but examples of specific management activities can be given.

- Practices aimed at increasing NPP: fertilization; genetically improved trees that grow faster (Peterson *et al.*, 1999); any management activity that enhances growth rate without causing a concomitant increase in decomposition (Stanturf *et al.*, 2003; Stainback and Alavalapati, 2005).
- Practices aimed at reducing R_h (*i.e.*, minimizing the time forests are a source to the atmosphere following disturbance): low impact harvesting (that does not promote soil respiration); utilization of logging residues (biomass energy and fuels); incorporation of logging residue into soil during site prep (but note that this could also speed up decomposition); thinning to capture mortality; fertilization.

Since NECB changes with time as forests age, if a landscape is composed of stands with different ages, then carbon gains in one stand can be offset by losses from another stand. The net result of these stand-level changes determines overall landscape-level carbon stores. Note that disturbance-induced R_h losses are typically larger than annual gains, such that a landscape where forest area is increasing might still be neutral with respect to carbon stocks overall. Thus, at the landscape level, practices designed to enhance carbon sequestration must, on balance, replace lower-carbon-density systems with higher-carbon-density systems. Examples of these practices include: reducing fire losses; emphasizing very long-lived forest products; increasing the interval between disturbances; or reducing decomposability of dead material.